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The Author.

“On the Production of Transient Electric Currents in Iron and Steel Conductors by Twisting them when Magnetised, or by Magnetising them when Twisted.” By J. A. EWING, B.Sc., F.R.S.E., Professor of Mechanical Engineering and Physics in the University of Tokio, Japan, now Professor of Engineering in the University College, Dundee. Received October 21, 1882.*

§ 1. A chance observation, made in the summer of 1881, drew my attention to the fact that when the ends of an iron wire are connected to the terminals of a galvanometer, a transient current will be observed if the wire be suddenly magnetised while it is held in a state of torsion, or suddenly twisted whilst in a state of longitudinal magnetisation. Further inquiry showed that these currents are satisfactorily explainable by reference to the results of more direct observations which have been made on the effects of stress on magnetism. They present, however, certain features of interest, and the examination of them, of which a condensed account is given below, may form a useful supplement to any direct investigation of the effects of stress on magnetic susceptibility and residual magnetism.

§ 2. A straight, moderately soft, well-annealed iron wire, 1 millim. in diameter and 34 centims. long, was placed horizontally in an E. W. position, with one end securely fixed and the other held by a twisting arm, by which any desired amount of torsion might be applied. The twisting arm was provided with a pointer, which travelled over a graduated circular dial. The ends of the wire were connected by long leading wires to a Thomson's mirror galvanometer of 0.25 ohm resistance, with a heavy mirror, which made it fairly suitable for ballistic work. Round the iron wire was a magnetising solenoid of 660 turns, 31 centims. long, in two layers, wound so as to have no longitudinal component parallel to the wire. In circuit with the solenoid was a single large Daniell's cell and a reversing key. The resistance of this

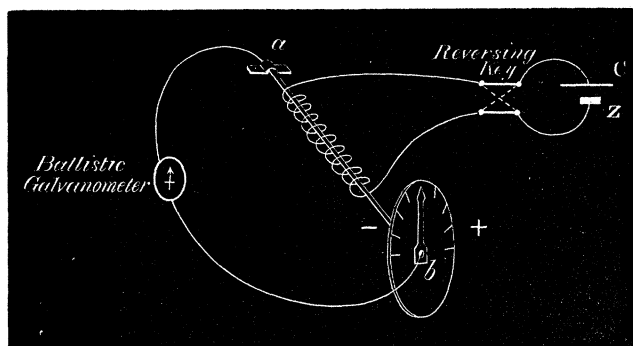
* This condensed version of a paper with the above title, read before the Royal Society, November 17, 1881 (see “Proceedings,” vol. 33, p. 21), together with a Supplementary Note received later, is printed by order of the Committee of Papers.—G. G. S.

circuit was 1.36 ohms and, if we assume the electromotive force of the cell to have been 1 volt, the magnetising force was therefore

$$4\pi \times \frac{660}{31} \times \frac{1 \times 10^8}{1.36 \times 10^9} = 20 \text{ c.g.s. units very nearly.}$$

The ideal diagram (fig. 1) will help in describing the directional relation of the transient currents, the magnetisation, and the torsion.

FIG. 1.



There *ab* is the iron wire, with the twisting-arm and dial-plate at *b*. The two directions of twist are distinguished by the signs + and -, the latter being used when the twist is that of a common screw. The two directions of the magnetising current will be called A and B; the connexions for A are shown by the full lines, and for B by the dotted lines. A has the effect of making the dial end (*b*) of the wire a nominal N. (*i.e.*, a "north-seeking") pole. A transient current will be called positive when it flows along the wire from *a* to *b*.

§ 3. When the wire was in a state of no torsion the closing of the battery circuit did not of course produce any current in the ballistic galvanometer; nor, when the wire was sensibly free from magnetisation, did twisting it produce any effect. But when the wire was first twisted negatively (like a common screw) and then magnetised by closing the circuit, A, a transient current flowed along it from *b* to *a*, that is, from N. to S. Reversal of the magnetising current from A to B, the wire being still held twisted, caused a transient current of twice the quantity of the first to pass in the opposite direction.

In like manner, if the magnetising current A was first made and the wire then twisted suddenly like a common screw, a transient current flowed along it from *b* to *a*, that is from N. to S., and similar currents were observed when, without maintaining the magnetising force in action, a permanently magnetised wire was suddenly twisted.

§ 4. The existence of these transient currents is due to the production of a state of circular magnetisation as the result of torsional stress and longitudinal magnetism acting jointly. To prove this, I substituted for the wire a long piece of iron gas-pipe, itself insulated, but carrying in its interior an independent copper wire, which was in circuit with the ballistic galvanometer. The gas-pipe was longitudinally magnetised by a surrounding solenoid. The making and reversing of a current in the solenoid whilst the pipe was held twisted, or the sudden twisting of the pipe during or after the operation of the magnetising force, gave transient currents along the insulated wire inside precisely similar to those which had been observed when the two functions of inducing magnet and conductor were both discharged by a solid iron wire. The pipe gave much greater currents, chiefly because of its greater size, but partly also because the metal in it was more advantageously disposed than in a solid rod, both as regards the stress and the subsequent inductive effect on the conductor inside.

§ 5. That longitudinal magnetisation combined with torsion should give rise to circular magnetism follows from Sir William Thomson's discovery that æolotropic stress develops an æolotropic difference of magnetic susceptibility in iron. When the wire or tube is twisted the stress is equivalent to pull and push along lines perpendicular to the radius and inclined at 45° to the direction of the length. Along one of these the magnetic susceptibility is increased; along the other, at right angles to that, it is diminished. The effect is to change the lines of induction, originally straight and parallel to the axis, into screws, whose circular components produce the transient currents now described. The direction of the currents is that corresponding to *increase of magnetism by pull*.

I shall now give a brief account of the experimental results, and afterwards point out their relation to the discoveries of Villari and Thomson on the effects of stress on magnetism, as well as to certain recent experiments of my own on the same subject.

§ 6. The wire described in § 2 was twisted oppositely to a common screw by turning the pointer through an angle of 60° to the side marked positive (see fig. 1). As the wire was initially free from any considerable magnetisation, this operation gave no transient current. The battery current A was then made, the wire being held twisted. This gave a positive transient current along the wire (from *a* to *b*), which produced a deflection of 39 scale divisions of the ballistic galvanometer. The throw of the galvanometer will be taken as giving, on an arbitrary scale, a measure of the circular magnetisation of the wire.

Then keeping the wire still twisted at $+60^\circ$, the current A was broken. This gave almost no transient current: in other words, the circular magnetism was scarcely at all affected by the removal of the

longitudinal magnetising force. Other experiments with wires of larger diameter and with a tube have shown that to remove the longitudinal magnetising force when the wire is twisted generally produces a very slight reduction of the circular magnetism, although in some instances it produces an actual increase (see § 22 below). In the present case the breaking of the magnetising current produced no effect at all comparable with that which was produced by its first establishment. Re-making the current after breaking also gave almost no sensible effect.

Reversal from A to B gave a transient current of -78 , showing that the circular magnetism changed to -39 , and repeated reversals of the current gave the same, or very nearly the same, effect.

§ 7. Again, if instead of twisting the wire first, and magnetising it when twisted, we apply either A or B at the zero of torsion, there is no effect. Let A be kept on, and let the wire be suddenly twisted to $+60^\circ$: there is then a transient current equal to about $+35$. The circular magnetisation acquired in this way is therefore somewhat less than that which was reached by twisting first and magnetising afterwards. If now, at $+60^\circ$ of torsion, we reverse from A to B, we have a transient current of -74 : in other words, the circular magnetism is changed from $+35$ to -39 . A subsequent reversal from B to A gives $+78$, and so on.

§ 8. If we next keep A made, and change the torsion suddenly from $+60^\circ$ to -60° , we get a current, not of -78 , but of only about -72 . A twist back from -60° to $+60^\circ$ gives a still smaller positive deflection, and successive repetitions of the same operation, under constant magnetising force, cause a gradual diminution of range, until, after many back and forth twistings, the transient currents are -64 , when the wire is twisted from $+60^\circ$ to -60° , and $+64$, when it is twisted from -60° to $+60^\circ$. This means that the circular magnetism is then changing between $+32$ and -32 , on the assumption that the effects are symmetrical on the two sides. That they were very nearly so in the experiment cited I have no doubt; there may, however, have been a slight set towards the side on which the first and greatest circular magnetisation occurred. If, after this steady state has been reached by successive opposite torsions, the battery is reversed from A to B at $+60^\circ$, a transient current of -71 shows that the circular magnetism is at once restored to its normal value of -39 .

§ 9. The foregoing results may be stated more clearly and shortly in tabular form, thus:—

Magnetising current.	Torsion.	Transient current.	Circular magnetisation.
Make A.....	Steady at $+60^\circ$	+39	+39
Reverse A to B.....	" " "	-78	-39
" B to A.....	" " "	+78	+39
With A on.....	$+60^\circ$ to -60°	-72	-33
" "	After several + and - twists, } $+60^\circ$ to -60° } -60° to $+60^\circ$ }	-64	-32
" "	" " "	+64	+32
Then, Reverse A to B.	at $+60^\circ$	-71	-39
" B to A.	"	+78	+39

Also, starting from a neutral state—

With A on.....	0° to $+60^\circ$	+35	+35
Reverse A to B.....	at $+60^\circ$	-74	-39
" B to A.....	" "	+78	+39

These figures show that if we call ± 39 the *normal* circular magnetisation proper to the given torsion (60°) and the given longitudinal magnetising force, then the first application or reversal of the magnetising force while the wire is held twisted develops the full normal value of the circular magnetism, whereas the first application or reversal of the torsion under constant magnetising force does not produce the normal value, but something less. Also that this defect of circular magnetism is increased by successive back and forth twistings, which finally cause the circular magnetism to oscillate between two considerably reduced values. After this steady state has been reached, a single reversal of the longitudinal magnetising force, the torsion being kept constant, suffices to produce the full normal value of the circular magnetism proper to the state so arrived at.

§ 10. If after being circularly magnetised by applying longitudinal magnetising force whilst it is held twisted, the wire be relieved of torsion by allowing the twisting arm to return suddenly, but without shock, to zero, a portion of the circular magnetism survives the removal of the stress which gave rise to it. Thus:—

Magnetising current.	Torsion.	Transient current.	Circular magnetisation.
Make A.....	At $+60^\circ$	+39	+39
With A on.....	$+60^\circ$ to 0°	-24	+15
Also, " "	0 to -60°	-48	-33

From the last observation it will be seen that the second step

(0° to -60°) brings us to the value -33 , almost identical with that which was reached in § 9 by twisting at once from $+60^\circ$ to -60° .

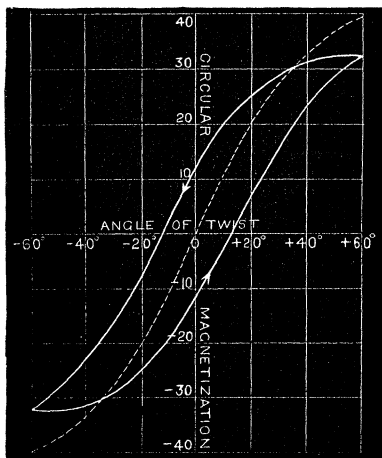
This tendency on the part of the circular magnetisation to follow at a distance instead of accompanying the changes of torsion is still more clearly shown if we divide the whole angle from $+60^\circ$ to -60° into several steps. The following figures give the transient current so obtained after the torsion had been reversed sufficiently often to bring the changes into a steady and sensibly cyclic state. The current A was kept on throughout.

Torsion.		Transient current.		Circular magnetisation.
-60° to $+60^\circ$	.....	$+64$	.....	$+32$
$+60$ „ $+30$	.....	-3$	.....	+29$
$+30$ „ 0	.....	-17	.....	-12
0 „ -30	.....	-28	.....	-16
-30 „ -60	.....	-16	.....	-32

with similar values for the return stages.

The full lines in fig. 2 give the relation of circular magnetisation to angle of twist during this cyclic operation. They show well how the changes of the former lag behind those of the latter.

FIG. 2.



§ 11. The same tendency towards persistence of previous state is exhibited whenever we change the magnetisation of a piece of iron or steel by the alternate application and removal of any kind of stress. It is exhibited also when magnetisation is changed by changing the magnetising force, when it appears as the characteristic ordinarily called retentiveness, to which the existence of residual magnetism is

ascribed. It also appears, as was shown first by M. E. Cohn, and afterwards independently by myself in a paper which I had the honour recently to lay before the Royal Society,* in the changes of thermoelectric quality which occur in iron when it is subjected to cyclic changes of stress. In the instances now referred to this lagging seems to be permanent as regards time, so that if it is to be ascribed to molecular friction, the friction to which it is due must resemble the friction of solids rather than the viscosity of liquids. To avoid much circumlocution it is convenient to give this lagging action a name, and accordingly I have called it *Hysterêsis* (from *ὑστερέω*, to come after, used either of place or time). This name may be properly applied not only in cases where, as here, the persistence of previous state appears to be permanent as respects time, but also in those cases where (as in the relation of strain to stress in a viscous material) the amount of lagging depends on the rate of change of the conditioning quality, and would disappear if that were indefinitely slow.

To define the new term more precisely, let there be given two qualities of matter, M and N, of which M is a function of N; then if when N is changed cyclically the corresponding changes of M lag behind the changes of N, we may say that there is "hysteresis" in the relation of M to N. The value of M at any particular point of the operation depends not only on the actual value of N but on all the preceding changes of that quantity, and by properly manipulating those changes any value of M within more or less wide limits may be found associated with a given value of N.

In all the instances of "hysteresis" mentioned above this further characteristic is present, that the range through which M varies becomes gradually diminished when a cyclic variation of N is repeated several times, and it would seem that only after an indefinitely large number of repetitions of the cycle of N do the changes of M also become exactly cyclic.†

§ 12. In the paper referred to above I showed that the action here called hysteresis, when it exhibited itself in the relation of thermoelectric quality to stress in a soft-iron wire, could be nearly, if not wholly, destroyed by mechanically agitating the wire during or after

* "Proceedings," vol. 32, p. 399.

† Objection may, perhaps, be taken to the coining of a new word on the ground that the term "retentiveness," already in use, expresses sufficiently nearly the same idea. In physics, however, retentiveness is limited by custom to denote the power of retaining magnetism when the magnetising force is removed, whereas one of the instances in which "hysteresis" has been noticed has, at least apparently, no connexion with magnetism. And unless the word retentiveness be used in a sense much less restricted than is now customary, it will not cover even those cases of "hysteresis" which occur in magnetic phenomena.

the change of stress. The same thing is true in the present case. After the circular magnetisation has been reduced from 39 to 32 by successive twistings between $+60^\circ$ and -60° under constant magnetising force, it can be at once raised again to 39 by tapping the wire vigorously. Again, if in making the steps $+60^\circ$ to 0° and 0° to -60° under constant magnetising force, we permit the wire to spring back freely to the zero of torsion and oscillate there (instead of making the twisting arm come against a stop which arrests vibration), we find that the two steps give nearly equal transient currents—in other words, that at the zero of torsion there is then almost no circular magnetisation.

§ 13. A still more effective way of restoring the circular magnetisation to its normal value after it has been affected by hysteresis is to change suddenly the longitudinal magnetisation of the wire. The molecular agitation so produced acts like mechanical vibration. Almost all trace of the effects of hysteresis vanishes if we simply break and remake the magnetising current in the solenoid. This is especially true of soft iron; with steel the effects of hysteresis are only partially removed by this means.

For example, let the circular magnetism be reduced to 32 by successive twistings between $+60^\circ$ and -60° under the A current, then if we break A and remake it, each of these operations gives a small positive transient current, the two together showing that the circular magnetism has risen to very nearly its full value of 39. Or, again, if after applying A at $+60^\circ$ we untwist to zero, keeping A on, there is a residual circular magnetism of +15: then let A be broken and remade, and each of these operations will give a negative transient current, the two together amounting as nearly as possible to -15, after which subsequent makes and breaks of the magnetising current will give no effect. If on the other hand we reach the zero of torsion from -60° with A on, the residual circular magnetism is negative, and in that case positive transient currents are produced when A is broken and remade. Generally, to remove and reapply, or better, to reverse the longitudinal magnetising force while there is no torsion, has the effect of removing any circular magnetisation which may have remained from previous operations.

§ 14. To determine the normal value of the circular magnetisation corresponding to different angles of twist, with the same longitudinal magnetising force, we have simply to bring the twisting arm to any angle, and, holding it there, reverse the magnetising current more than once. The first reversal wipes out the effect of previous operations and sets up the normal state of circular magnetisation; the second reversal changes that from + to -, and so gives a transient current half of which is to be taken as the measure of the circular magnetisation. The following observations were made at different

angles of twist from 10° to 60° , the currents being observed after at least one previous reversal of the magnetising force.

Angle of twist (scale reading).	Transient current given on reversal of battery.		Circular magnetisation. = $\frac{\text{mean}}{2}$
	A to B	B to A	
+ 10°	-25	+25	$12\frac{1}{2}$
-10	+21	-21	$10\frac{1}{2}$
+20	-41	+43	21
-20	+42	-38	20
+30	-55	+56	28
-30	+54	-52	$26\frac{1}{2}$
+40	-67	+67	$33\frac{1}{2}$
-40	+66	-64	$32\frac{1}{2}$
+50	-73	+75	37
-50	+71	-72	36
+60	-78	+80	$39\frac{1}{2}$
-60	+76	-78	$38\frac{1}{2}$

The same results are shown graphically in the dotted line of fig. 2 ; comparison of it with the full lines of the same figure will serve to show the part played by hysteresis in the changes of circular magnetisation which are caused by changes of stress.

§ 15. The torsions which have been hitherto spoken of were well within the limits of elasticity. When the angle of twist was increased beyond 60° the transient currents given on reversal of the battery were not greatly augmented. They reached a maximum at about 90° , at which angle the torsion began to produce distinct permanent set, and for greater angles they diminished slightly. Moreover, after the wire was twisted beyond its elastic limit, and allowed to come back to its new zero of torsional stress, reversal of the longitudinal magnetism then gave transient currents of opposite sign to those which were given while the stress which caused the set was in operation ; the reason probably being that the wire, though then free from torsional stress, had acquired a helical quality with respect to magnetic inductive susceptibility, the susceptibility being less along the lines of permanent extension than in other directions. The lines of induction were therefore screws of opposite sign to the lines of permanent extension. Again, effects of the same sign as those observed would be given by permanent twist if permanent extension produced a state in which the electrical conductivity of the iron was less along than across the lines of strain. After being twisted to $+360^\circ$ the wire was allowed to spring back : its new zero of stress was at $+125^\circ$. There, after several reversals, B to A gave -7, and

A to B gave +7. By restoring 5° of positive torsion a state was reached in which reversals of the battery gave no transient currents.

§ 16. The effects which are obtained by twisting and untwisting after the longitudinal magnetising force is removed are somewhat more complex than those already described, on account of the fact that a gradual shaking out of the residual magnetism takes place, which is not, however, complete even after many twistings. For example:—

	Transient current.	Circular magnetisation.
At $+60^\circ$, reverse A to B.	+76	+38
Break A	sensibly 0	+38
$+60^\circ$ to 0°	-18	+20
0 „ -60°	-19	+1
-60° „ 0	+4	+5
0 „ $+60^\circ$	+12	+17
$+60^\circ$ „ 0	-4	+13
0 „ -60°	-8	+5
-60° „ 0	+4	+9
0 „ $+60^\circ$	+8	+17
$+60^\circ$ „ -60°	-11	+6
-60° „ $+60^\circ$	+11	+17

Ten more complete twistings; then

$+60^\circ$ to -60°	-9	+16
-60° „ $+60^\circ$	+8	+8

It is interesting to notice that the circular magnetisation has, so to speak, received a permanent set to the side on which its earliest and greatest value lay.

§ 17. Another experiment, to show the production of circular out of residual longitudinal magnetism:—

	Transient current.	Circular magnetisation.
Make and break A at 0° ...	0	0
Then, 0° to $+60^\circ$	+18	+18
At $+60^\circ$, remake A	+20	+38

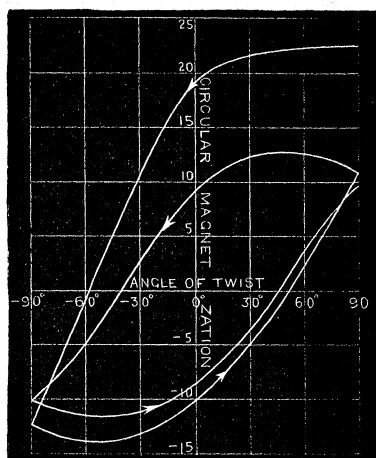
§ 18. The following table shows the relative amounts of circular magnetism developed in an iron wire (the wire of § 2), with one constant amount of torsion (60°) by different intensities of longitudinal magnetising force. It will be noticed that a maximum of effect is passed at about 15 or 16 c.g.s. units.

Longitudinal magnetising force. c.g.s. units.	Transient currents given on reversal of magnetising current.		
	A to B	B to A	Mean.
1.25	- 2	+ 2	2
1.64	- 3	+ 3	3
2.36	- 7	+ 7	7
3.20	-15	+15	15
3.64	-21	+21	21
4.2	-33	+32	32.5
5.0	-46	+45	45.5
6.1	-59	+57	58
8.0	-71	+70	70.5
11.3	-82	+80	81
14.0	-86	+84	85
15.8	-86	+85	85½
17.1	-86	+84	85
19.7	-84	+83	83.5
23.7	-75	+75	75

A continuation of the same experiment showed that when the magnetising force was increased the transient currents continued to diminish, falling almost to zero, but did not become reversed. Even with a wire of very soft iron a magnetising force of over 100 c.g.s. units still gave effects of the same sign as the above.

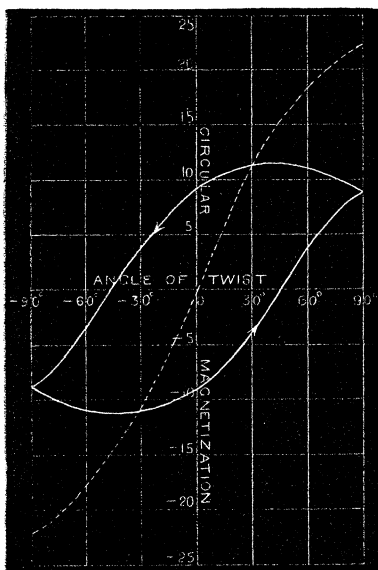
§ 19. Similar series of experiments were made with a piece of pianoforte-steel wire in its ordinary temper. Fig. 3 shows how the

FIG. 3.



circular magnetisation of the steel wire, starting from the normal value for $+90^\circ$, was altered by successive twistings between $+90^\circ$ and -90° under the action of a constant longitudinal magnetising force of 20 c.g.s. units. It exhibits very strikingly the lessening of range brought about by successive twistings, which has been already alluded to (§8) as occurring (though to a less extent) in iron. Finally, after several twistings, a sensibly cyclic set of changes was instituted which is shown by the full lines in fig. 4. [The "normal" curve

FIG. 4.



(see § 9) is shown by the dotted line in the same figure.] A remarkable feature here is that when the direction of twisting is reversed the first effect is to continue the same kind of change of circular magnetism as was going on before. The curve rises before it begins to fall, and *vice versa*.

Many other observations have been made, which it is needless to describe, since they are all in obvious agreement with the explanation already offered. It only remains to point out this agreement in the case of those features of the experiments where it is not at once evident.

§ 20. It was discovered by Villari,* and rediscovered by Sir W. Thomson,† that if an iron rod in a magnetic field be subjected to pull

* Wiedemann's "Galvanismus," II, § 499.

† "Phil. Trans.," Part I, 1879, p. 55.

parallel to the lines of force its magnetism is increased, provided that the magnetising force does not exceed a certain value, but decreased if the magnetising force does exceed that limit. Experiments of my own, not yet published, have shown that the Villari reversal of the effect of pull occurs at a particular value of the magnetisation rather than at a particular value of the magnetising force. They have also shown that, apart from its influence on magnetic susceptibility, pull increases residual magnetism when that is not too strong (this Villari had observed), and further, that the changes of either induced or residual magnetism produced by changes of stress always exhibit the action I have called hysteresis, with the characteristic described in § 11, viz., diminution of range in successive operations, with an approach to a cyclic condition when a cyclic change of stress is repeated. The lagging of magnetic change is just such as might, on Weber's theory of magnetic induction, be ascribed to a frictional resistance opposing the rotation of the magnetic molecules; further, it is capable of being, in great part, destroyed by mechanical vibration.

The experiments now under review exhibit the same actions occurring when we deal with the combined pull and push stress set up by torsion.

§ 21. In view of the discovery of Villari and Thomson I expected that with a high magnetising force the signs of the transient currents would be reversed, so that they would then indicate decrease of magnetism by pull. This did not occur (§ 18) apparently for the following reason. My own direct experiments show that moderate* pull increases the magnetism of iron only so long as that is less than (very roughly) about three-fourths of its limiting value. Now, when a longitudinally magnetised rod is twisted, the pull and push of which the stress is made up act not on the full magnetisation but on components of it inclined at 45° to the axis. The intensity of magnetism on which the stress acts is therefore rather less than three-fourths of the whole, and hence, even when we increase the magnetising force indefinitely, the action still occurs below, though very near to, the Villari critical point. Under these circumstances the transient currents become much diminished in amount, but they preserve the same signs as they have when the magnetising force is small, the signs, namely, which correspond to increase of magnetism by pull.†

* The precise point of reversal depends, amongst other things, on the amount of pull applied.

† Sir W. Thomson (*loc. cit.*, § 229) has applied his discovery of the effects of stress on the magnetic inductive susceptibility of iron to explain G. Wiedemann's observation that an iron rod traversed longitudinally by an electric current becomes a magnet when twisted, and expresses his surprise at finding no reversal of the poles when a strong current was used; but if the above explanation of the non-reversal

§ 22. It has been mentioned that the removal and re-application of longitudinal magnetising force acting on an iron wire under torsion produced almost no change of the circular magnetism, and that when a small change was visible, it had sometimes the apparently anomalous character of increase of circular magnetism with removal of longitudinal magnetising force. My experiments show that the residual magnetism of soft annealed iron is generally very great, amounting to as much as 80 or even 90 per cent. of the induced magnetism, provided that care be taken, by the use of a very long rod or a ring magnet, to prevent the existence of any self-demagnetising force when the inducing force is withdrawn (a condition present in these torsion experiments), and also provided that mechanical disturbance be avoided, which, if it occurs, will remove by far the greater part of this large residue. Now any change of circular magnetism which takes place when the longitudinal magnetising force is withdrawn from a twisted wire must be due to the fact that the effect of torsion in producing circular magnetism is either less or greater on the residual than on the total longitudinal magnetisation. The two are so nearly equal that but little change occurs, and in general, when the longitudinal magnetising force has not been very intense, the change is of the nature of a diminution. But when the longitudinal magnetisation has been very strong, the 45° components of it, on which the effects of pull and push are felt, may approach so closely to the Villari critical point that the reduction of them which takes place when the magnetising force is removed makes them more susceptible to the action of stress, and so causes an increase of circular magnetism.

§ 23. To complete the explanation of the results, allusion need be made to only one other point. It was mentioned in § 19 that when by successive twistings from one side to the other, a cyclic condition was established in steel, then at the beginning of each release from torsional stress a slight increase of circular magnetism took place (see fig. 4). My experiments on the effects of stress on magnetised wires show that at the beginning of each loading or unloading the initial change of magnetism is *nil* relatively to the initial change of stress, if great care be taken to avoid mechanical disturbance. When there is any disturbance at the beginning of the change of load, its effect is to make the magnetisation approach the value which it would assume under vibration. In the torsion experiments the changes of stress were necessarily effected suddenly, and must have been accompanied by some slight vibration. This affords a sufficient explanation of the

of the transient currents be correct, it applies equally to Wiedemann's result. There, too, the intensity of magnetisation on which the differential effect of pull and push is felt, being $\frac{1}{\sqrt{2}}$ of the whole circular magnetism, cannot be increased sufficiently to cause the Villari reversal.

point now under consideration ; for in the observation shown in fig. 4, the initial effect of beginning to release the wire from stress, instead of being *nil*, was in fact just that which a small amount of vibration would cause.

§ 24. The fact that sudden torsion gives a transient current along a magnetised iron or steel rod was observed by Matteucci as early as 1858. An account of his observations is given by Wiedemann ("Galvanismus," II, § 484), from which it appears that when an iron rod under the influence of longitudinal magnetising force was twisted like a common screw, the current flowed from south to north. The direction stated is opposite to that taken, under similar conditions, by the currents in my experiments. A possible explanation of this discrepancy may be found if we suppose that in Matteucci's experiments the Villari critical point had been passed, which might have been the case if he applied strong torsional stress in conjunction with strong magnetisation. For it has been shown by Sir W. Thomson,* and confirmed by my own experiments, that the Villari critical point comes earlier with strong than with weak stresses. With the moderate stress used by me, reversal of the effects did not occur even with very high magnetising forces, but it is possible that by using more powerful torsion Matteucci may have brought his rods into the condition which would give decrease of magnetism by oblique pull. This suggestion is borne out by his observations with hard steel, of which it is said that when the magnetising current was broken, the transient currents produced by torsion changed their signs after the residual magnetism had been partly shaken out by the first twistings, showing apparently a passage through the Villari critical point as the magnetisation was reduced.

Matteucci has also remarked that the currents become constant only after several back and forth twistings. Curiously enough he says that a twisted rod gives no current when it is magnetised, but it is not unlikely that this (certainly erroneous) observation may have been due to an accidental omission to notice the effect of the first closing of the magnetising circuit after the rod was twisted. Subsequent openings and closings of the circuit do give scarcely any effect.

§ 25. By using a telephone in place of a ballistic galvanometer, Professor Hughes has observed the production of transient currents in a twisted iron wire by making and breaking a current in a surrounding solenoid, and he has described in a recent series of papers† this as well as many other closely related results. For example, he placed the iron wire in the battery circuit, and connected the telephone, to the external solenoid. Sounds were then obtained

* *Loc. cit.*, §§ 211 and 244.

† "Proc. Roy. Soc.," vol. 31.

by rapidly interrupting the current through the wire. This (which I have verified with a ballistic galvanometer) is a direct consequence of Wiedemann's discovery alluded to in a footnote to § 21 above.

§ 26. Apart altogether from the magnetic origin to which the transient currents described in this paper have been assigned, another cause probably contributes in some small degree to the production of the observed results. From Sir William Thomson's discovery of the effects of stress on electrical conductivity it follows that an originally isotropic conductor will, when under torsion, possess a helical quality with respect to electrical conductivity, and it has in fact been shown experimentally by Professor W. G. Adams and Mr. J. T. Bottomley that a brass tube, conveying a current longitudinally, becomes when twisted equivalent to a conducting helix. Hence when the longitudinal magnetism of a twisted iron rod (forming part of a circuit) is altered, a transient current will be induced in the helical lines of greatest conductivity by the magnetic change of the interior portion of the rod. The direction of greatest resistance in iron is (probably) that of pull, and the lines of greatest conductivity will therefore be helices opposite in sign to the twist of the rod. Magnetisation will therefore give a current from S. to N. when the twist is that of a common screw. The actual transient current, however, flows from N. to S. Moreover it is clear that the development of a helical quality with regard to conductivity will not explain the fact that the transient currents pass a maximum when the current in the solenoid is strengthened, nor apply at all to the gas-pipe experiment of § 4. It has been suggested to me that another more recondite partial origin of the transient currents given when a magnetised iron rod is twisted may be looked for in the fact that the diminution of longitudinal magnetism brought about by torsion induces a current in the magnetising solenoid, which again reacts on the helical lines of conductivity in the rod itself,—an idea which was perhaps present with Professor Hughes when he spoke of the transient currents as “tertiary.” It is safe to say that these and perhaps other influences enter into the production of the effects which have formed the subject of this paper; at the same time it may be affirmed with confidence that the phenomena, as they are observed, find a perfectly satisfactory and sufficient explanation in the setting up of a state of circular magnetisation by the influence of torsional stress on the existing longitudinal magnetism and on the susceptibility to magnetic induction.

Supplementary Note to the Original Paper. Received
August 30, 1882.

In the original paper under this title, communicated to the Royal Society on September 7th, 1881, it was suggested that the phenomena were due to the production of a state of circular magnetisation by the action of twisting stress on longitudinal magnetisation, the effect of twist being to produce a difference of magnetic susceptibility in the two directions of pull and push, inclined at 45° to the axis. Recent experiments of my own on the effect which pull has on the magnetic susceptibility and residual magnetism of iron (an account of which will be given separately) confirmed this conjecture; and, guided by the light which they threw on the subject, I have now made a short supplementary examination of the effects of torsion, which has shown that the conjectural explanation is perfectly satisfactory.

To show that the transient currents produced by twisting a magnet are due to the development of circular magnetisation, I substituted for the iron or steel wire used in former experiments an iron gas-pipe, itself insulated but carrying along its interior an insulated copper wire which was in circuit with a ballistic galvanometer. The gas-pipe was longitudinally magnetised by a surrounding solenoid. When the pipe was twisted, a transient current passed along the wire in its interior. Another transient current was given when the longitudinal magnetisation was reversed, the state of twist remaining constant. By this arrangement, in brief, all those phenomena could be reproduced which were described in the paper as exhibited when the two functions of inducing magnet and conductor were both discharged by a solid iron wire. The transient currents given by the tube were much more powerful, partly because the position of the conductor was more advantageous than when conduction was taking place throughout the twisted metal itself, but chiefly because of the relatively large size of the tube. By winding the insulated wire in the centre so that it passed several times through the tube, the effects were proportionately increased.

In the paper it was shown that when the longitudinal magnetising force was increased, the transient currents given by reversing that force while the wire was kept in a constant state of twist passed a maximum when (with one specimen) the value of the force was 15 c.g.s. units, after which the effects diminished slowly as the force was raised to 24 c.g.s. units, that being the highest value then used. The effects were such as to correspond to *increase* of magnetism along the lines of pull. From the discovery of Villari and Thomson that with a certain value of the magnetising force the effect of pull on magnetisation becomes reversed, we might expect the signs of the

transient currents to change if the magnetising force were sufficiently increased. Recently I have examined the effects with very high values of the longitudinal magnetising force. The transient currents are then exceedingly small, but they obstinately refuse to become reversed, even when the magnetising force is as much as 100 c.g.s. units. The effects still correspond to greater magnetisation along the lines of pull.

The explanation of this seeming anomaly lies in the fact that the Villari reversal of the effects of stress depends on the intensity of magnetisation rather than on the value of the magnetising force, and that the stress acts here only on a component of the whole magnetisation. I find that in soft iron, the effect of a moderate amount of pull is to give greater susceptibility so long as the magnetisation does not exceed about three-fourths of its limiting value. With a greater stress the reversal comes earlier, and with a very small stress it comes later. Now, suppose that we apply to a soft-iron wire a powerful magnetising force and thereby approach the limit of magnetisation. When we twist the wire, the directions of pull and push are inclined at 45° to the direction of magnetisation, and the stress

therefore acts on $\frac{1}{\sqrt{2}}$, or about seven-tenths of the whole intensity of

magnetisation. Hence pull ought still to increase (though very slightly) the magnetic susceptibility along the lines of pull, and the circular magnetisation ought still to have the same direction as it had when the magnetising force was small; and this is what actually occurs.

In the paper, it was noticed that when the magnetising current was interrupted while the wire was held in a constant state of twist, there was scarcely any change of the circular magnetisation. I now find that although in general the circular magnetisation decreases very slightly in these conditions, nevertheless it occasionally increases when the longitudinal magnetising force is removed. This happens in soft iron when that force is very high, and its occurrence is in complete agreement with direct observations of the effects of pull on magnetism. It means that the effect of pull is then greater on the 45° component of the residual magnetism than on the same component of the temporary magnetism, and this is the case when the affected component of the temporary magnetism is near that value at which the Villari reversal occurs. The following figures give an observed instance of this action in a very strongly magnetised soft-iron wire which was held in a constant state of twist. Calling the two directions of the magnetising current A and B, and the two directions of circular magnetisation + and -, we have :

	Ballistic throw.		Circular magnetisation.
Reversed, A to B	+ 8	....	+ 4
„ B „ A	— 8	....	— 4
Broke A	— 9	....	— 13
Made B	+ 17	....	+ 4
Broke B	+ 9	....	+ 13
Made A	— 17	....	— 4

Here the circular magnetisation was greater in the ratio of 13 to 4 when the differential effect of torsional stress was exerted on the (comparatively small) amount of residual than on the (comparatively large) amount of temporary longitudinal magnetism.

FIG. 1.

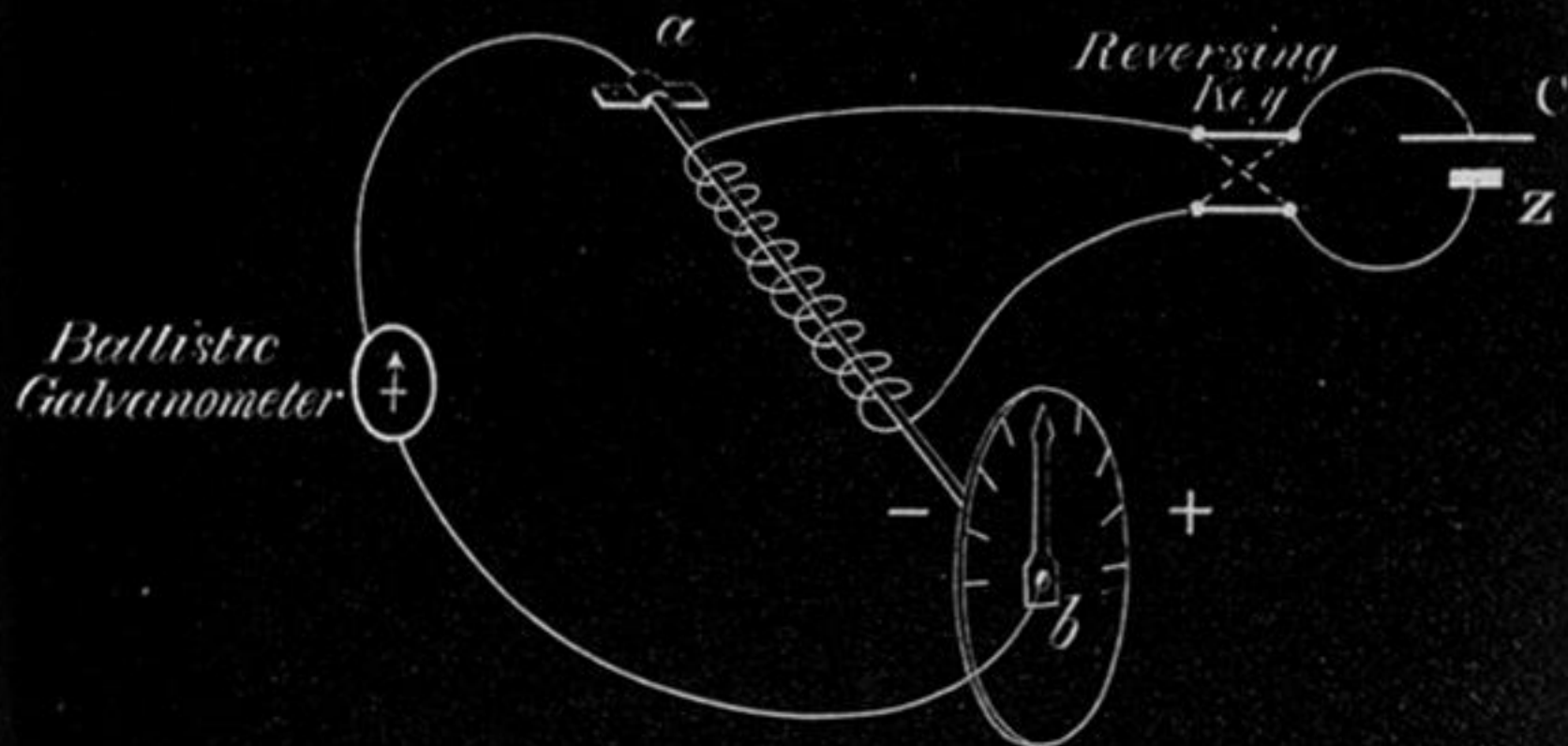


FIG. 2.

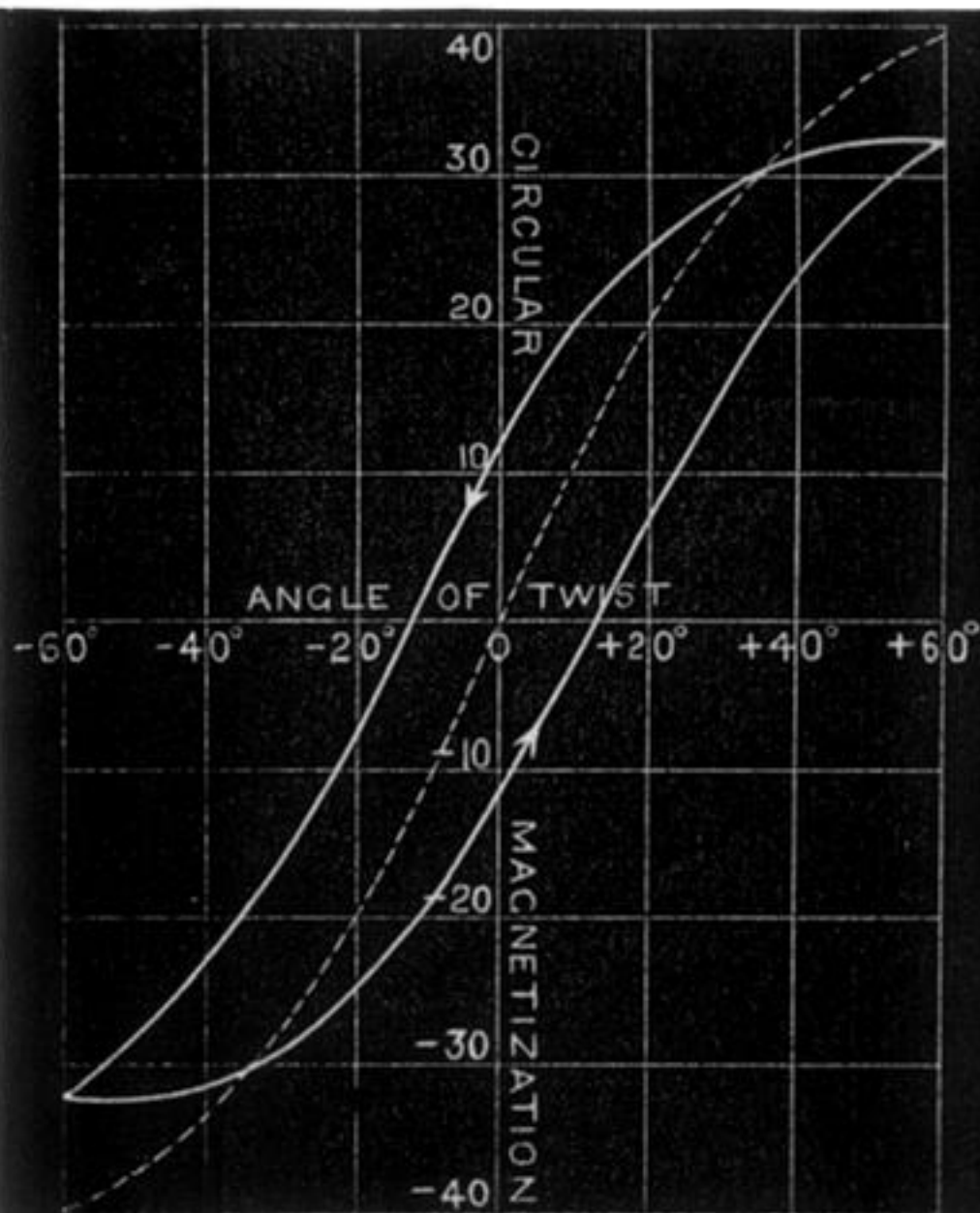


FIG. 3.

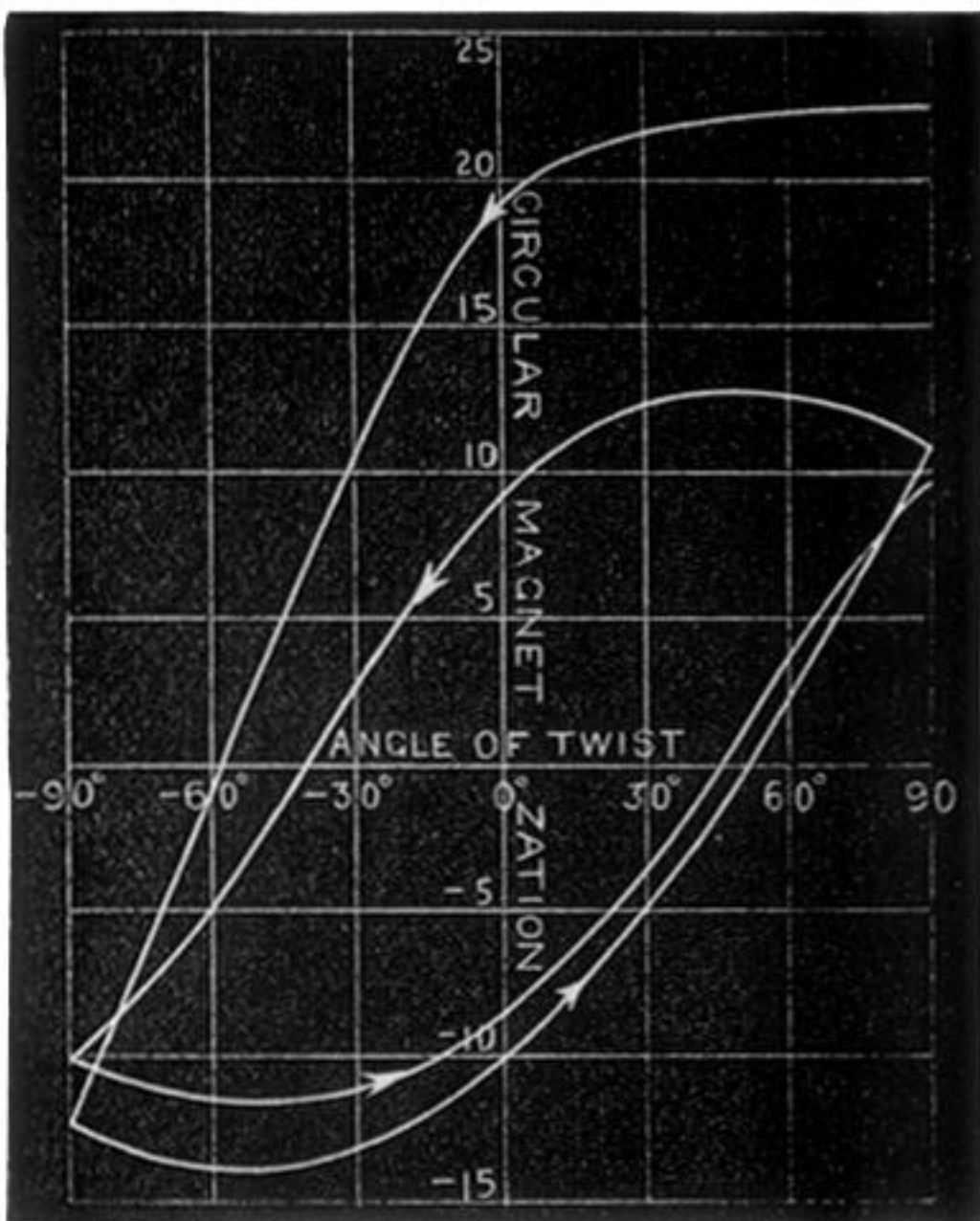


FIG. 4.

